Exploring the Mysteries of the Cosmos on the MOST Microsatellite Mission

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Abstract. The MOST (Microvariability and Oscillations of STars) astronomy mission under the Canadian Space Agency's Small Payloads Program is Canada's first space science microsatellite and is scheduled to launch in June 2003. The MOST science team will use the satellite to conduct long-duration stellar photometry observations in space. The primary science objectives include: measuring light intensity oscillations in solar type stars; determining the age of nearby "metal-poor sub-dwarf" stars, which will in turn allow a lower limit to be set on the age of the Universe; and detecting the first reflected light from orbiting exoplanets and using it to determine the composition of their atmospheres. To make these measurements, MOST incorporates into a microsatellite design a small (15 cm aperture), high-photometric-precision optical telescope and a high performance attitude control system that is revolutionary in its pointing accuracy for a microsatellite. A key hurdle that the MOST mission had to overcome was that of access to space. MOST as initially conceived was designed to launch as a secondary payload aboard a Delta II rocket carrying Canada's Radarsat-2 mission. However, subsequent delays in the Radarsat-2 program have pushed its launch to the end of 2004 or beyond. Access to space was extremely important to the MOST mission because of the revolutionary science that is being done. Consequently, the Canadian Space Agency contracted with Eurockot to provide launch services using a "Rockot" launch vehicle launching from Plesetsk, Russia. As we prepare for the launch in June 2003, the paper will present a summary of the science goals of the mission, will highlight the progress of the integration team in preparing the satellite for launch, and will reflect on the impact that changing launch vehicles has had on the satellite in our quest for access to space.

Introduction

The MOST (Microvariability and Oscillations of STars) astronomy mission under the Canadian Space Agency's Small Payloads Program is Canada's first space science microsatellite and is scheduled to launch in June 2003. The MOST science team will use the satellite to conduct long-duration stellar photometry observations in space. The primary science objectives include: measuring light intensity oscillations in solar type stars; determining the age of nearby "metal-poor sub-dwarf" stars, which will in turn allow a lower limit to be set on the age of the Universe; and detecting the first reflected light from orbiting exoplanets and using it to determine the composition of their atmospheres. To make these measurements, MOST incorporates into a microsatellite design a small (15 cm aperture), high-photometric-precision optical telescope and a high performance attitude control system that is revolutionary in its pointing accuracy for a microsatellite (see Figure 1).

One of the key challenges for the MOST microsatellite team has been access to space. MOST was initially to launch as a secondary payload accompanying the Radarsat-2 satellite. Delays in the Radarsat-2 program have pushed its launch into 2005. In order to gain quicker access to space, the Canadian Space Agency contracted with Eurockot Launch Services to provide a launch scheduled for 30 June 2003 from the Plesetsk Cosmodrome in Russia.

The paper begins with a description of the science goals of the MOST satellite. These will be shown to have led to a particular choice of orbit and launch vehicle to make space accessible for this microsatellite. This is followed by a description of the satellite design, and the impact that changing launch vehicles to obtain faster access to space had
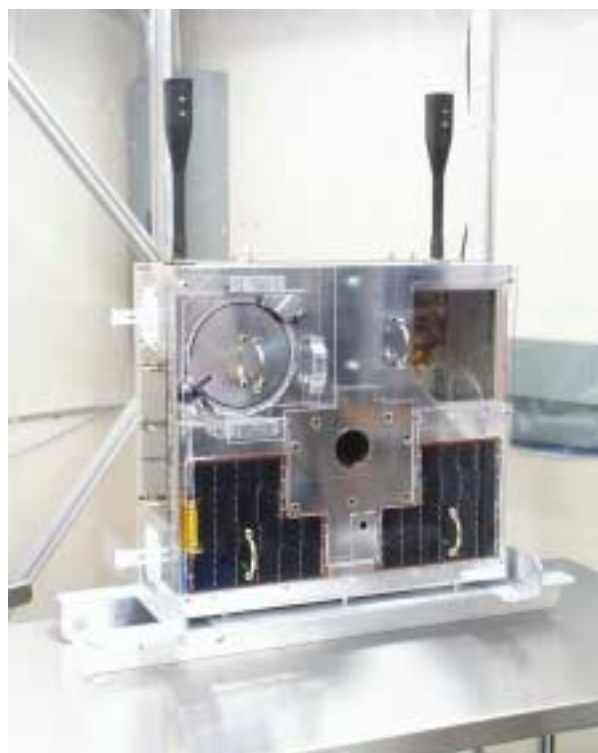
Figure 1: The MOST Microsatellite (with protective covers)

on the MOST program. Finally, the present status of the MOST program is discussed with launch scheduled for 30 June 2003.

Scientific Goals

Size doesn't always matter. Stellar seismologists exploit extremely tiny surface vibrations of stars, detected through brightness oscillations with amplitudes of a few parts per million, to probe stars' hidden interiors and ages and address big questions such as "What is the age of the Universe?") We don't need a big telescope to study many of the Sun's nearer neighbours in the Galaxy, which are bright enough to provide large photon fluxes and high signal-to-noise. However, atmospheric turbulence plus the day/night cycles inherent to single-site ground-based observing mean that a telescope must be in space. Even there, we don't necessarily need a big budget, if we take advantage of proven

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optical and detector technology and recent advances in microsatellite attitude control.

Until recently, performing optical astronomy experiments from a low-cost microsatellite (mass < 100 kg) was considered unfeasible because of the poor pointing possible from a platform with such small inertia (approx. ± 2°). In 1997, anticipating new microsat attitude control technology being developed by Dynacon Inc., a team of astronomers and aerospace engineers first proposed to the Canadian Space Agency (CSA) a project to obtain astronomical photometry of unprecedented precision from a microsatellite. In the next year, MOST (Microvariablity and Oscillations of STars / Microvariabilité et Oscillations STellaire) was selected to be Canada's first science microsat, as part of the CSA Small Payloads Program. Additional funding was provided by the Ontario Research and Development Challenge Fund, the Natural Sciences and Engineering Reseach Council (NSERC), the Ontario Centre for Research in Earth and Space Technology and the Universities of Toronto, British Columbia and Vienna.

MOST features a small optical telescope (aperture = 15 cm) equipped with a CCD photometer designed to return unprecedented
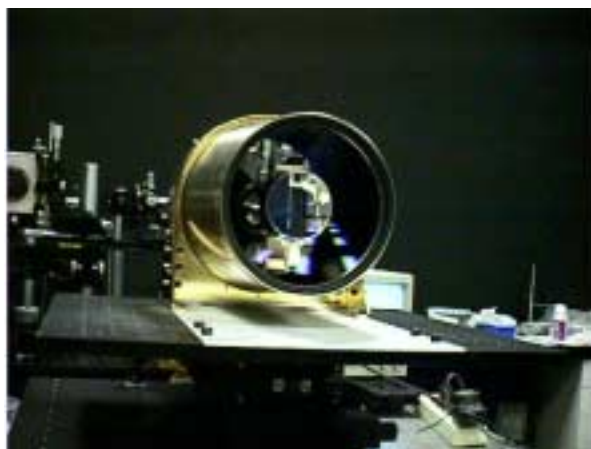

Figure 2: The MOST Telescope (15-cm Aperture)

photometric precision ($\Delta L / L \sim 10^{-6}$) and frequency resolution ($\Delta v \sim 0.1$ μHz) on stars other than the Sun. Given the fact that this instrument (see Figure 2) will be carried aboard a microsat bus about the size and mass of a suitcase, the Canadian public has come to know the MOST mission as the "Humble Space Telescope."

Probing Mysterious Planets: Following in Galileo's Footsteps

MOST was originally designed to detect rapid brightness oscillations in Sun-like stars, to seismically probe their interiors. However, once the project had passed the critical design
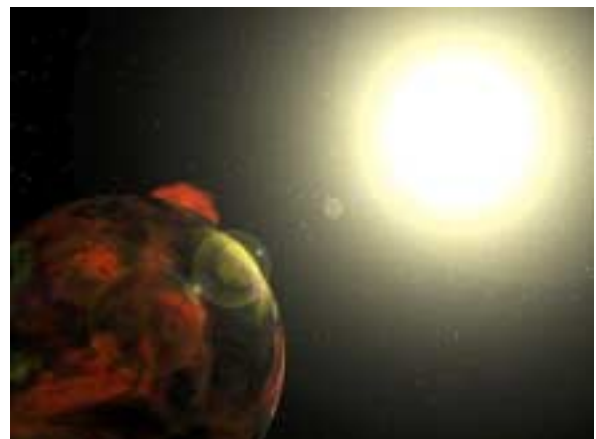
Figure 3: An Artistic Rendering of an Exoplanet

phase, it was realised the MOST instrument was more sensitive and versatile than originally expected in Phase A. It also had the potential to detect reflected light from some of the giant planets recently discovered to be orbiting other nearby stars. The amount of light reflected and scattered back to Earth by such an exoplanet (Figure 3) would vary during the planet's orbit, as it goes through illumination phases like those of the Moon or of Venus, as first observed telescopically by Galileo in the early 1600's.
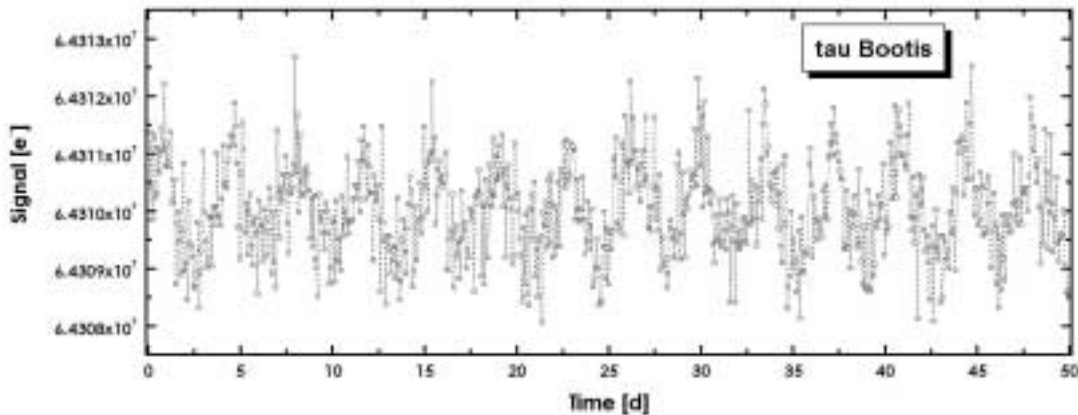
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*Figure 4: Simulated MOST "observations" of a star with an
exoplanet orbiting every 3.3 days*

Therefore, in Phase C of the project, the MOST team added an exciting new science application, without changing the hardware or software design, or the selected orbit, and at no added cost.

The amplitude and shape of the reflected light curve of an exoplanet depends on the planet's size, its orbital inclination and eccentricity, and most importantly, its atmospheric composition (which determines its albedo). However, the exoplanet signal is very subtle – about a part in 105 relative to the brightness of its parent star – with orbital periods of a few days for the exoplanets with the smallest orbits. Simulations by Green et al. (2003) indicate that MOST should be able to detect this signal for exoplanet systems like 51 Pegasi (the first solar-type planetary system to be discovered) and tau Bootis (Figure 4).

MOST would be the first instrument in history capable of detecting these signals and giving direct information about the atmospheres of these mysterious worlds. At the same time, data on the oscillations of the parent stars would specify the ages of these stellar/planetary systems – an important test of models of how these planets formed and evolved.

Why go to space?

It is not currently possible to perform photometry at the precision of 1-10 ppm required for solar-type seismology or exoplanet light curves. For example, if the Sun were observed as a point source (like a distant star), then the net amplitude of its integrated oscillations would be only a few cm/s in velocity and a few micromagnitudes in brightness. Such levels lie about two orders of magnitude below present detection limits for ground-based measurements (although efforts to improve the spectroscopic limits are underway). In fact, even the solar oscillations have been detected in brightness only from space, by the ACRIM bolometer aboard the Solar Maximum Mission, the IPHIR experiment aboard the Phobos probe, and the VIRGO irradiance instrument on the SOHO satellite.

To be able to perform seismology of Sun-like stars and the detection of reflected light from exoplanets requires both:

1. Very precise detections of photometric signals as low as a few ppm; and

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2. Long, nearly uninterrupted monitoring of each star for weeks at a time.

Neither is easy to achieve but getting both simultaneously is virtually impossible from the surface of the Earth.

Scintillation noise

Turbulent cells of air at altitudes of about 10 km in the Earth's atmosphere have slightly different temperatures that change their refractive indices. As these cells, of order 10 cm across, are carried over the beam of a telescope, they modulate the intensity of starlight randomly and rapidly. This is the cause of star "twinkling"; i.e., atmospheric scintillation. Scintillation is the dominant source of photometric noise in measurements of oscillation amplitudes below about 0.1% (1000 ppm) and at timescales of only a few minutes. This noise term depends on the position of the star relative to the horizon, the exposure time, and the altitude and aperture of the telescope. Scintillation noise decreases with increasing aperture. As the light collecting area becomes larger, the incoming stellar signal is integrated over a larger number of turbulent cells and their effects begin to average out more effectively.

Consider a set of 60-second photometric measurements from the summit of Mauna Kea, Hawaii (altitude = 4200 m) of a bright star (apparent visual magnitude V = 3, about the brightness of the North Star) at the zenith. To reduce the scintillation noise to order 10^{-5} in a single reading, you'd need a telescope almost 100 metres across!

Continuous monitoring

From the Earth, an astronomer has only limited options if she wants to monitor a star continuously for times much longer than half a day:

1. Observe from a site near one of the poles during prolonged night.

2. Operate a network of telescopes spread in longitude around the globe so that at least one of the sites can observe the star in darkness at all times.

(Both these options require the astronomer to be somewhat religious, since she has to pray for clear weather everywhere for weeks at a time.)

The first approach is frustrated by the less-than-ideal conditions for stellar photometry in the Arctic and Antarctic, although there are plans for a South Pole stellar observatory which may experience photometric conditions in the near-infrared. The latter approach has been used successfully by the Global Oscillation Network Group (GONG) to study the low-amplitude velocity oscillations of a very bright source (the Sun), and by the Whole Earth Telescope (WET) to study the relatively high-amplitude (10%) oscillations of faint sources (pulsating white dwarfs). Both approaches are expensive of money, facilities, and human resources.

However, neither of these approaches can avoid the scintillation limit. Even if five of the world's existing 4-metre-class telescopes in Hawaii, the continental U.S., Chile, Spain, and Australia were dedicated to searching for solar-type oscillations in a bright star (V = 3) for over 6 weeks, they would still fail to detect the 4-ppm signal represented by the Sun's oscillations, or even a signal 10 times larger associated with the reflected light of a close-in giant exoplanet.

The "Humble Space Telescope"

The MOST instrument is a Maksutov telescope fed by a flat "periscope" mirror which allows it to sit in the allowed volume of the instrument bay. The Maksutov optics gives MOST a wide field (about 2° in diameter) so that it can serve as a guiding star sensor for the microsat attitude control as well as a science instrument. The telescope feeds starlight to a pair of frame-transfer CCDs: one for guiding, one for science. Through frame transfer, the integrations can be stopped without the need for a mechanical shutter. In fact, the MOST instrument is designed to have **no** moving parts (to reduce cost and increase reliability). The structure is athermal, so that the optics maintain focus across the wide temperature range between alignment on the ground and the orbital environment.

Light from a given target star is directed onto a Fabry lens, which will project an image of the telescope's pupil onto the CCD: a doughnut with an outer diameter of about 40 pixels. The reasons for the Fabry imaging are three-fold: (1) Spreading the starlight over many pixels reduces the sensitivity of the photometry to pixel-to-pixel sensitivity variations across the CCD, and to damaged pixels and columns. (2) For bright stars, the extended image avoids saturation of the individual pixels. (3) As the microsat wobbles in space by up to ± 10 arcsec rms, the pupil image will remain fixed on the same pixels, moving by no more than 0.1 pixel. This will make it possible to obtain ultraprecise photometry down to amplitudes of a few ppm for stars as faint as V ~ 6 (the limit of visibility for the naked eye).

The Right Orbit for the Science

To achieve the photometric sensitivity and Fourier frequency resolution required to meet the MOST science objectives, the ideal MOST orbit would maximize the size of the Continuous Viewing Zone (CVZ) and minimize the stray Earthlight that could enter the telescope aperture. However, the choice of orbit must also be tempered by practical considerations of the radiation environment, up/downlink capability, and of course, cost.

The ideal orbit for such a stellar seismology / exoplanet mission would be far from Earth, with a very large CVZ and little stray Earthlight interfering with the photometry. However, for a low-budget microsat mission, geostationary or L2 orbits are not affordable. So the MOST team was forced to consider Low Earth Orbit (LEO). The most common equatorial LEOs for space astronomy missions, like the Hubble Space Telescope, have inclinations which result in fairly small CVZs at the celestial poles, severely restricting target selection. Therefore, a polar orbit was selected which would provide a large equatorial CVZ.

To fully profit from staring continuously at a target for weeks, the science requirement was >80% duty cycle for observations, with a goal of >90%. This means that solar eclipses by the Earth's limb and passage through the South Atlantic Anomaly (SAA) must inhibit <10% of observations within the CVZ. Solar eclipses lead to loss of solar sensing and power as well as thermal shock to MOST. In operation, the normal to the rear solar panels must lie within 30° of the direction to the Sun if the satellite is not to lose too much power for science operations. Radiation damage to the electronics and detectors is also a consideration, as well as periods when high fluxes of cosmic ray strikes could confuse star tracker readings. The SAA expands with altitude, increasing the potential "black-out" time (when observations may be inhibited) for higher orbits. On the other hand, the higher the orbit the less the limb of the Earth cuts

into the CVZ to introduce parasitic light and the shorter Earth eclipses will be at one or other of the solstices.

Careful estimates were made of the expected MOST radiation environment with SPACE RADIATION 4.0 (available from Space Radiation Associates, www.spacerad.com) and they indicated a significant but not serious degradation of CCD performance (dark current increase, hot pixels, reduced charge transfer efficiency etc.) during the first year in orbit for altitudes from 700 to 900 km. Most degradation is inflicted by passage through the high radiation concentrations of the SAA. A 5 mm thickness of aluminum shielding would largely prevent any degradation except by the most energetic particles. The Invar used in the main tube of the telescope structure and aluminum in the camera housing provides an effective 8 mm of shielding. In fact, much more shielding than this would induce a flux of secondaries more damaging than the primaries themselves.

As a compromise, an altitude of ~820 km has been chosen. This gives MOST a CVZ about 54° wide, spanning a range in declination from +36° to -18°. This region of the sky encompasses many bright solar-type stars, including several known to have large exoplanets in orbit around them. The maximum dwell time of a star in the middle of this CVZ is ~60 days. Such a long series of photometry with high duty cycle would resolve frequency spacings as small as about 0.1 μHz, needed to accurately estimate stellar ages from the oscillation spectrum.

Another important factor in a stellar photometry mission in LEO is scattered Earthlight. The secondary payload accomodation envelope baselined for MOST would not permit a large external baffle. Although the internal baffles have been designed to reduce parasitic light by a factor of 10^{-12}, light from the bright limb of the Earth would severely affect the photometry. Therefore, one of the most critical specifications for the MOST orbit was that it be Sun-synchronous and dawn-dusk, so the telescope could always look out over the shadowed limb of the Earth. (An orbit with a Local Time of Ascending Node (LTAN) crossing of 18:00 was eventually selected because the associated CVZ contained more targets of primary science interest.) The added bonuses of this orbit are thermal stability (no thermal snaps crossing the terminator except during brief eclipse seasons) and efficient use of the solar arrays on the rear face of the satellite (which would always be directed towards the Sun).

A three-stage Russian Rockot will inject MOST into a near-polar orbit (period ~100 min) inclined at approx. 98.7° to the equator, from the Plesetsk Cosmodrome in northern Russia. Launch is scheduled for 30 June 2003. The elements of the proposed orbit are given in Table 1.

Table 1: MOST Orbital Elements (Planned)

Altitude of Apogee	844.392 km
Altitude of Perigee	827.528 km
Semi-Major Axis	7206.960 km
Inclination	98.696°
Orbital Period	6088.9 sec
Local Time of Ascending Node (LTAN)	18 h 00 min 0.00 sec

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Orbit and launch vehicle selection

The Radarsat-2 orbit, a dawn-dusk sun synchronous orbit, presented an excellent opportunity for the MOST mission. Subsequently the satellite was designed with this orbit in mind. This launch was initially scheduled for November 2001. However, it was plainly obvious early in the design of the MOST spacecraft that Radarsat-2 would not launch on schedule. Early in the Radarsat-2 program, the decision was made to change the spacecraft bus. The planned bus was dropped in favour of a new satellite bus that would be built by Alenia. This introduced a delay of at least 18 months to the scheduled launch date while the design and build of the MOST spacecraft proceeded. Further delays have resulted due to both payload and satellite bus developments. The Radarsat-2 launch is now scheduled no sooner than early 2005; a delay of more than 3 years.

This experience highlights one of the major issues regarding access to space for small satellites. Small satellites (i.e. low cost satellites) do not dictate launch schedule. For the most part, inexpensive satellites such as MOST can only afford to launch as secondary payloads. The launch schedule, however, is determined by the primary payload. In our case this could have resulted in a delay of more than 3 years in a program that was anticipated to be only 3 years (excepting operations). This would have been disastrous in terms of both cost and scientific return for the mission.

The strategy for designing the MOST spacecraft has been to use a small team of dedicated professionals. The primary reasons for this are to maintain a flexible team that can rapidly adapt to changing situations, and to keep the overall labour costs low. The larger the workforce, the less flexible it is. However, a small team in which every member is critical can be a double-edged sword. If a delay in the program occurs, every member is still critical and needed for the success of the program. Therefore the cost of the program will tend to increase by a greater percentage for a small team that must be maintained than for a large team that can be trimmed to a minimum number of members during delays. Considered as a whole, it is still cheaper to use the small team than to use the large team, but the longer a program is stretched out, the less benefit is provided in terms of cost.

In terms of scientific value, a delay of 3 years would have a significant impact. MOST is the first astronomical photometry mission of its kind. It is the first, but not the only mission. The French COROT mission and the ESA Eddington mission have similar goals only with larger satellites. Therefore there is a certain urgency in getting the MOST satellite into space to perform its ground breaking science.

As a result of the expected and continuing delays in the Radarsat-2 mission, the Canadian Space Agency in 2000 began to search for alternative launch opportunities. Fortunately for small satellites, there are presently a large number of launch opportunities on small Russian launch vehicles. The CSA consulted with the Dnepr, Cosmos and Rockot launch providers amongst others, and entered negotiations with Eurockot Launch Services of Bremen, Germany to launch on the converted Russian SS-19 "Rockot" launch vehicle. It is on the Rockot launch vehicle that MOST is scheduled for launch on 30 June, 2003. This may be 18 months behind as originally scheduled with Radarsat-2, but it is still more than 18 months ahead of the presently expected Radarsat-2 launch.

It is at this point that a small, integrated team was particularly useful, because in order to

launch on the "Rockot" some key design changes had to be made. The small team was able to adapt well to these changes

Satellite Design Overview

The MOST satellite design originates from trying to fit as large a telescope as possible, all the electronics to interface with the telescope, the satellite bus equipment that allows the storage and transmission of the science data to the ground, the ACS hardware that is required to maintain better than 25 arcsecond pointing accuracy for the telescope, and a power system to provide enough power to the satellite, all into a package that can meet the requirements for launch as a secondary payload on a Delta II launch vehicle (with Radarsat-2 as the primary payload). It probably bears little resemblance to the satellite design that would have resulted had a launch on the Rockot been planned from Day 1. However, that is the nature of microsatellite design.

The telescope is a 15cm diameter aperture Maksutov telescope that is described in detail in Walker et. al [2]. A periscope mirror allows the long axis of the telescope to lie perpendicular to the aperture of the telscope and therefore fit into the Delta II secondary payload physical constraints. Attached to the telescope, separate from the satellite bus structure, is a two stage passive cryocooler that is capable of maintaining the focal plane of the telescope at a temperature of –40°C. Covering the aperture of the telescope is a door that is designed to actively close to protect the instrument focal plane from direct sunlight.

The satellite structure is based on a tray stack design. The structure consists of aluminum trays that house the satellite's electronics, battery, radios, and attitude actuators. These trays are stacked (see Figure 5) forming the structural backbone of the satellite. To this backbone, the science instrument, a 15 cm aperture Maksutov telescope is mounted with its barrel parallel to the axis of the stack. Six aluminum honeycomb panels, acting as substrates for solar cells and carriers for attitude sensors, enclose the tray stack/telescope assembly, forming the box seen in Figure 1. An actuated telescope door mounted on the star facing side of the satellite protects the telescope focal plane from direct stares at the Sun should the satellite tumble or lose attitude lock.
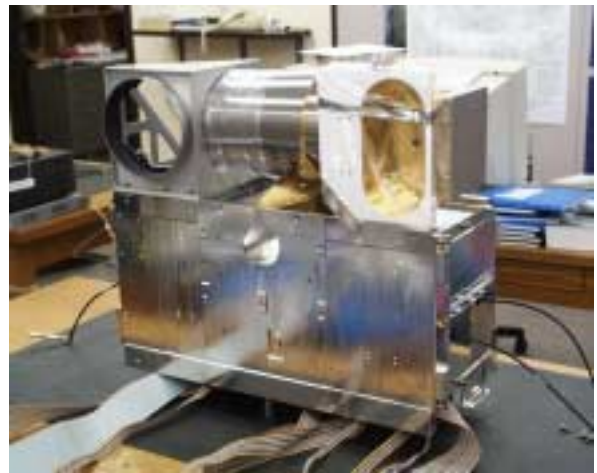

Figure 5: The MOST Tray Stack and Telescope

Satellite Electronic Architecture

The satellite electronic architecture is shown in Figure 6. The housekeeping computer, which is central to the design and the figure, is an off-the-shelf product that has been modified to meet MOST requirements. Based on a V53 processor, the computer's crystal frequency has been increased from 9 MHz to 29 MHz to accommodate the processing demands of the mission. It interfaces with the rest of the satellite through a custom interface card that provides power, serial and digital I/O connections. The housekeeping computer's main tasks include receiving, executing, and distributing commands and/or files uploaded

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MOST Architecture
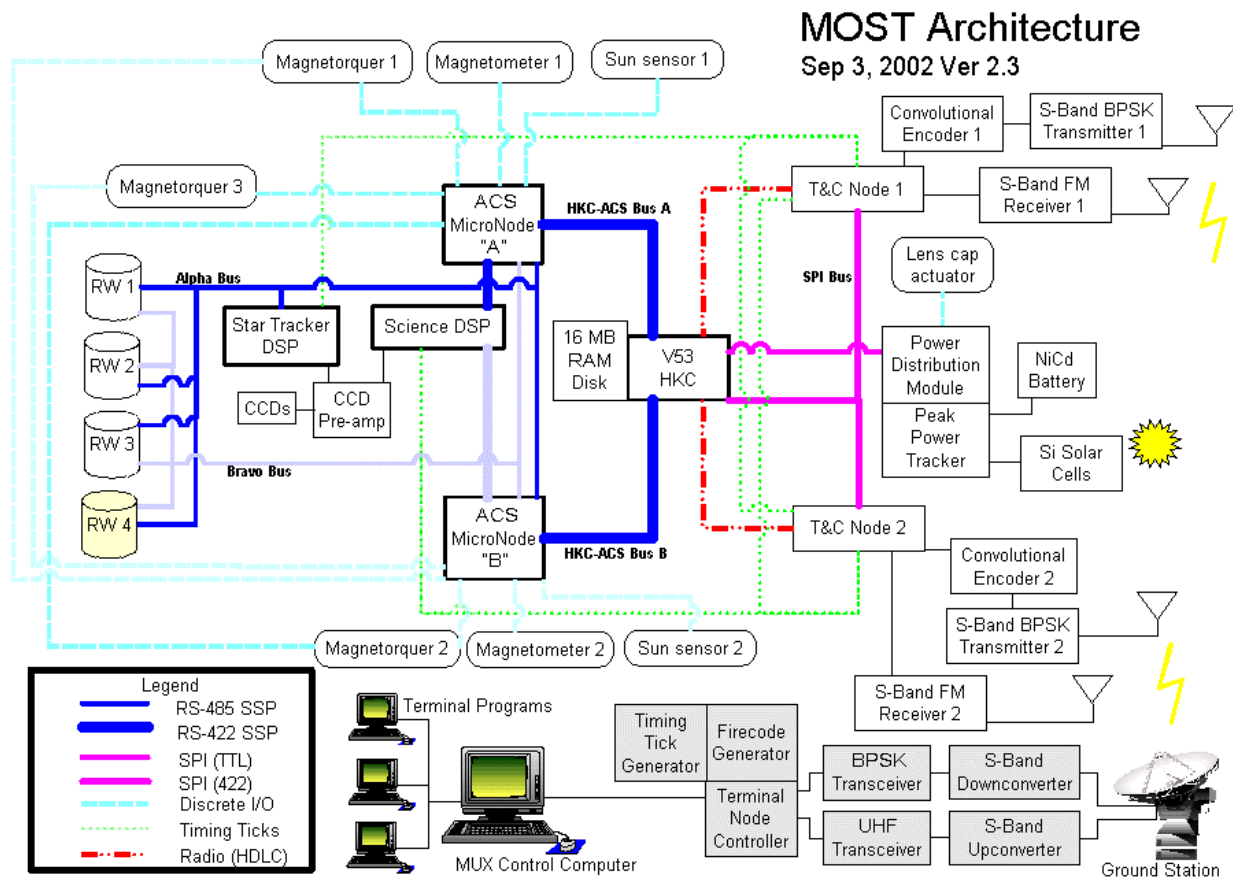### Sep 3, 2002 Ver 2.3

Figure 6: The MOST Architecture

from the ground, and collecting and transmitting engineering and science data to the ground.

In the figure, roughly from the V53 to the right, the satellite design is typical of AMSAT based designs. It consists of the main housekeeping computer (V53), radio transmitters and receivers including support electronics, and the power system for the satellite.

MOST employs two 0.5W RF output BPSK transmitters and two 2W FM receivers. All radios operate at S-band frequencies. Sufficient downlink margin is maintained by using a 0.5 rate convolutional code, implemented on a custom board. On the

uplink, FM receivers provide a simple, robust, and low-cost means to talk to the satellite. Both receivers and transmitters connect to custom telemetry and command nodes that serve as modems and telemetry collection devices. To maintain omni-directional coverage, one receiver/transmitter pair is located on either side of the satellite, connected to quadrifilar antennas. Each radio operates on its own frequency. Thus, the appropriate transmitter is selected based on which receiver is being used.

The power subsystem is based on a centralized switching, decentralized regulation topology. Power regulation occurs through switching power supplies to maximize conversion efficiency (power is very limited

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in a satellite of this size – 35W in fine pointing operations and only 9W in safe-hold or tumbling operations). While this poses EMC/EMI challenges for the Science DSP computer that must read its CCD Array with almost zero noise, these challenges have been met.

The power system switches are controlled via the housekeeping computer. Two levels of load shed protect the satellite from unrecoverable battery drainage, allowing contingency operations to resume in safe-hold mode. All power lines have overcurrent protection.

In terms of energy storage, a NiCd battery provides power during eclipses and supports peak power draws from equipment such as the transmitters. High-efficiency silicon solar cells on all sides of the satellite generate energy to recharge the battery and provide power for fine pointing and safe-hold operations. Peak power tracking hardware and software (run by the housekeeping computer) maximize the available power to the satellite subsystems.

To the left of the V53 computer is the equipment that makes the MOST satellite unique for a microsatellite in the scientific contribution that it can make. These are the electronics to support the telescope, and the ACS hardware and electronics. The ACS equipment consists of magnetometers, sun sensors, and a star tracker for sensing, and magnetorquers and reaction wheels for actuation. The key developments here have been the use of reaction wheels for three-axis attitude control, and the development of a star tracker that is a fundamental part of the science telescope. Combined these enable the satellite bus to maintain pointing accuracy of less than 25 arcseconds.

Science and star tracker images are taken on dual 1024x1024 CCD arrays that share the focal plane of the telescope. Each CCD is connected to a pre-amplifier, and to analog and digital electronics boards (Figure 7). These boards are based around a Motorola 56303 DSP, and provide digital control and Analog to Digital conversion of the signals from the CCDs. The instrument computers are designed to provide nearly noiseless CCD readings while tolerating disturbances from switching power supplies.

Figure 7: MOST Instrument Computer

There are four attitude control modes for the satellite:

Safe-Hold: . The satellite is essentially power positive in all practical orientations. Therefore, this is an uncontrolled state in which there is no active attitude control. In this mode, the focus is nominally on commissioning or recovery operations.

Detumbling: This mode involves using the magnetometers and magnetorquers to implement B-dot control to slow the tumble rate of the satellite so that coarse pointing control can be executed. Normally this is used after kick-off from the launch vehicle.

Coarse Pointing: After the satellite is detumbled, the ACS uses sun sensors and magnetometers to determine the spacecraft attitude, while using reaction wheels to control the attitude to orient the main solar array towards the Sun and to roughly point in the direction of science interest. The magnetorquers are used to desaturate the reaction wheels.

Fine Pointing: The ACS the star tracker to determine spacecraft attitude to an accuracy of three arcseconds. The reaction wheels are used to control the attitude. The magnetorquers are used to desaturate the reaction wheels.

The attitude control computers (ACS nodes) are also based on the Motorola 56303 DSP. The DSP acts as the fundamental processing unit that runs the ACS software. The computers provide analog control of the magnetorquers, power and analog to digital conversion of the magnetometer and sun sensor signals, as well as RS-485 connections to the main housekeeping computer, the reaction wheels (which contain their own microcontroller) the star tracker and science DSP boards. Nominally, only one ACS node is operational. The second is designed as a cold spare to add redundancy where it was practical.

All computers have Error Detection and Correction (EDAC) hardware and software to correct for bit errors induced by radiation. Single event latch-ups are corrected by power cycling the affected device.

To ensure that components within the satellite operate at suitable temperatures, a combination of passive surface treatments are used including aluminum, gold, and silver teflon tapes. In the event that the satellite enters a cold state due to a disadvantageous attitude relative to the Sun, resistive heaters are used to keep the battery and trays sufficiently warm. During fine pointing operations, a passive radiator cools the telescope focal plane so as to minimize thermal noise in the CCD readout

Ground Stations

Three ground stations in Toronto, Vancouver and Vienna will be used to download data from MOST. The primary control station will be in Toronto (Figures 8 and 9), while the secondary stations (Vancouver and Vienna)

Figure 8: MOST Ground Station

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Figure 9: Antenna System at UTIAS/SFL

will be controlled and coordinated over the Internet. Although the basic mission can be accomplished with just one ground station, additional science data can be acquired using the secondary stations.

The stations used for MOST communications are based on an amateur radio core station operating at VHF and UHF frequencies. They are upgraded with S-band transverters and BPSK transceivers connected to a 2-m parabolic antenna (downlink) and a 45 element loop yagi (uplink). The antennas are mounted on a heavy-duty, precisely controlled rotator located atop a 20-foot tower (Figure 9).

The ground station radios are connected to a custom terminal node controller (combination modem and serial communications controller) which is in turn connected to a computer that coordinates multiple terminals each running interface software for specific components on the satellite (see Figure 6). Through this system, terminal users have a virtual link to their satellite hardware of interest. The terminal node controller also generates "firecodes" or emergency commands to reset satellite hardware. A "timing tick" generator is used to maintain knowledge of clock drift in

the instrument computers so as to accurately time tag science observations.

Impact on Design as a result of change of launch vehicle

The change from Delta II to Rockot launch vehicle had no significant changes on the electrical design of the satellite. However, there were important changes that were needed in the structural design, and these had an important effect on cost and schedule of the
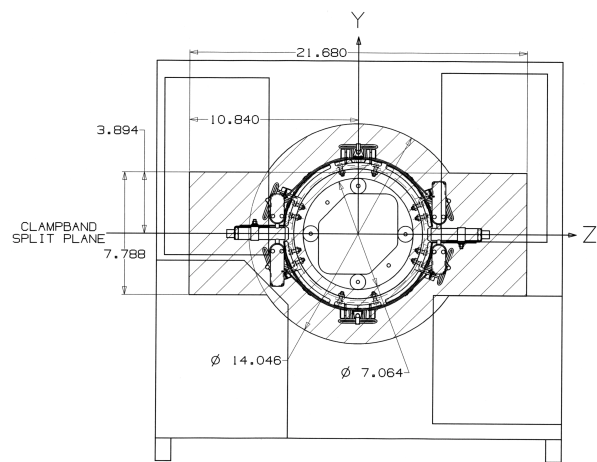

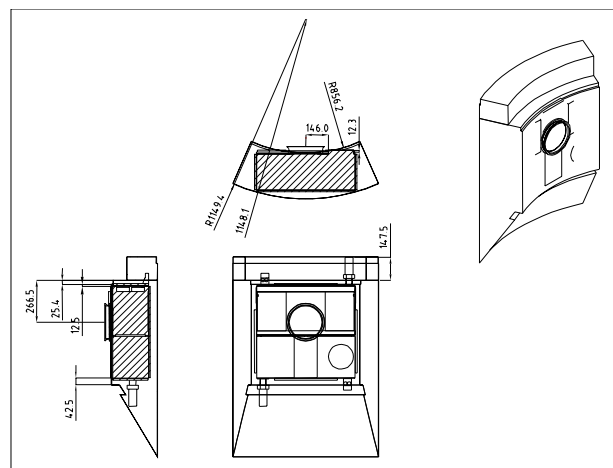
Figure 10: Delta II Marmon Clamp Attached to MOST

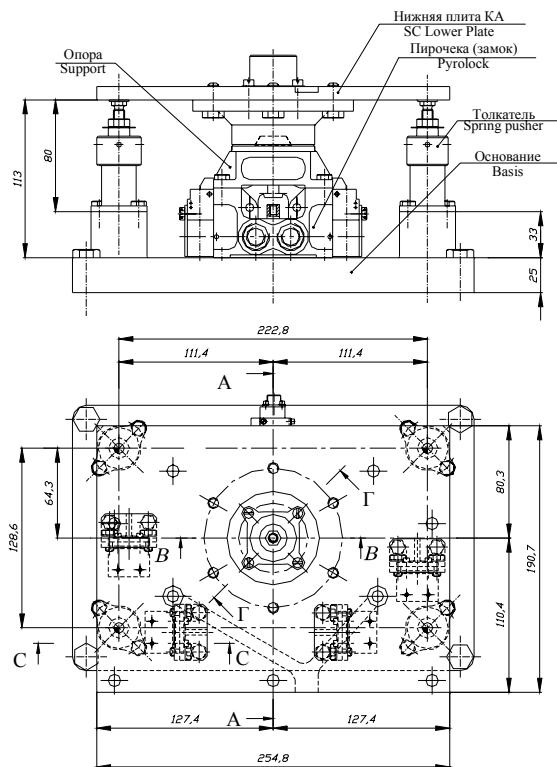*Figure 11: MOST in Delta II Secondary Envelope*

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Figure 12: Rockot Pyrolock System

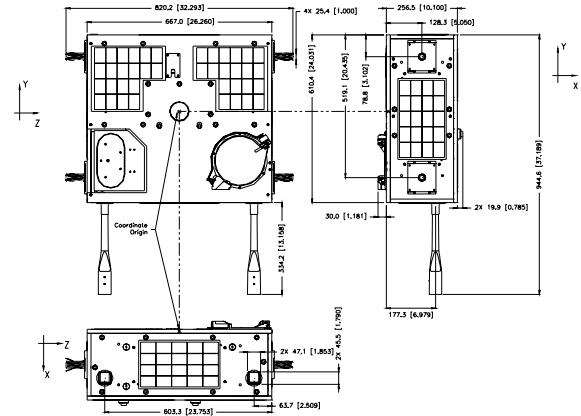*Figure 13: MOST Modified to Accommodate Rockot Pyrolock*
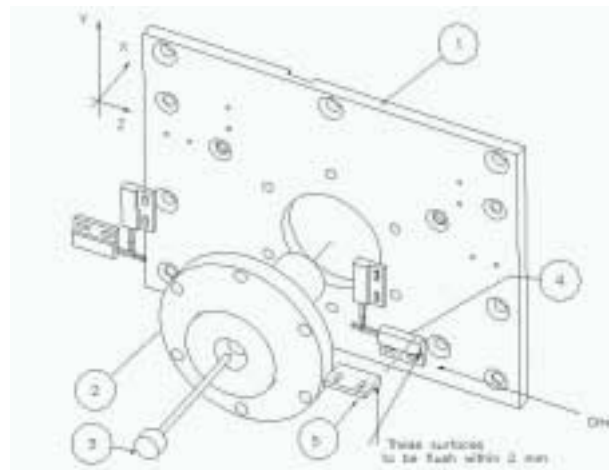
Figure 14: Payload Attach Fitting to Accommodate Pyrolock System

program. For our purposes, the primary difference between accommodation on the Delta II and the Rockot launch vehicles is the payload adapter interface. The Delta II uses a 9-inch Marmon clamp (see Figures 10 and 11), while the Rockot uses a pyrolock mechanism (Figure 12). The pyrolock mechanism has as very different interface to the satellite. It consists of a central rod that pulls the spacecraft towards the launch vehicle. There are 3-4 hardpoints that contact the satellite to oppose the preload that is provided by the central rod. At these hardpoints, there are spring pushers to provide separation forces once the central rod is released by the pyro-mechanism.

While negotiations were in progress with Eurockot on the launch contract, work was frozen on the central five trays of the tray structure, and the –X panel of the spacecraft that interface with either the Marmon clamp or the pyrolock mechanism. This resulted in approximately 6 months of delay in the program and the costs that are associated with the delay. (See Figures 13 and 14 for the resulting MOST and payload attach fitting designs.)

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Program Status

The MOST spacecraft began environmental test on October 15, 2002 at the CSA's David Florida Laboratory in Ottawa, Canada and completed environmental testing on January 18, 2002. Environmental testing consisted of spacecraft vibration testing, EMI testing, and TVAC testing.

The spacecraft was put through a series of low-level sine, high-level sine, sine burst and random vibration tests to qualify the satellite for launch on the Rockot vehicle. For the random vibration tests, a force-limited vibration technique was used to avoid overtesting of the satellite (See Scharton [3]).

The spacecraft is nominally unpowered on the launch vehicle. However there is a small circuit that monitors the state of non-contacting separation sensors that is active during launch. The spacecraft was tested to ensure that the launch vehicle RF environment would not result in EMI pickup on the separation sensor lines. This is to ensure that the satellite does not mistakenly engage prior to actual separation from the launch vehicle.

The Thermal Vacuum testing was performed to verify that functionality of all of the satellite equipment over the expected thermal range in a vacuum environment. TVAC tests were performed at the each of the extremes of the thermal range that are expected on orbit. At each of these extremes all of the equipment that is required at these temperatures was functionally tested. In addition, operational scenarios were tested. These included testing during changing thermal enviroments that result from the satellite entering and exiting eclipse once per orbit.
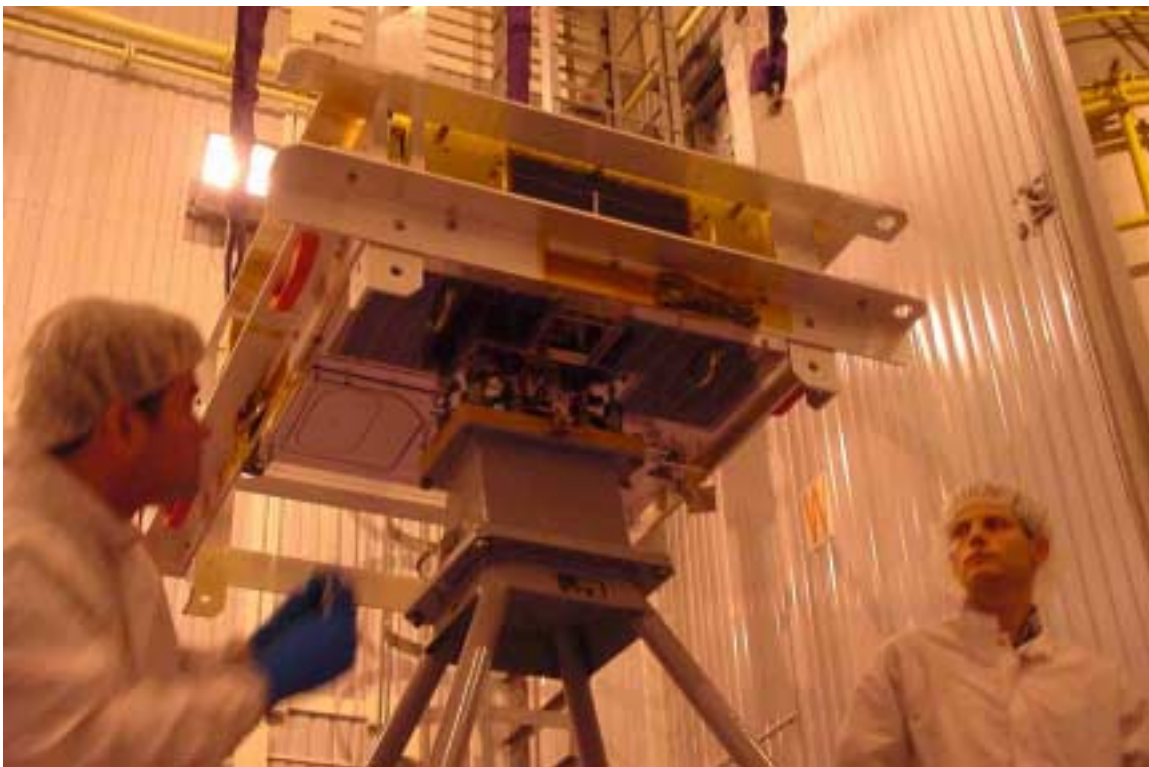
Following environmental testing, the

Figure 15: MOST at the Plesetsk Cosmodrome. Shown here is a mating check.

spacecraft completed its functional testing. The functional test plan covers all aspects of unit functionality within the context of spacecraft-level operation. This included testing of the attitude control system which could not be tested during TVAC. The ACS is functionally tested using a series of tests performed with the spacecraft on a single axis air bearing. On the single-axis air bearing, the detumble, coarse pointing and fine pointing modes of the satellite were checked out and shown to work functionally. Performance testing was not possible in a 1-g environment.

The MOST satellite program passed its flight readiness review on 7 May 2003.

On 13 May 2003 the MOST satellite and GSE was shipped from Toronto, Canada to begin its long journey to the Plesetsk Cosmodrome in Russia. The launch campaign began on 26 May 2003 at the Plesetsk Cosmodrome where the satellite was given a final checkout. The satellite was mated with the separation system designed and built by the Khrunichev State Research and Production Space Center (a 49% partner in the Eurockot consortium). Figure 15 illustrates the activities in the Integration Hall of the Plesetsk Cosmodrome.

Integration with the launch vehicle is scheduled to take place on 14 June 2003, with the launch scheduled for 30 June 2003.

Figure 16 shows our team at the Plesetsk Cosmodrome. The sign says Russian Space Forces, Plesetsk Cosmodrome.

Figure 16: The MOST Team at the Plesetsk Cosmodrome. From left to right, Jaymie Matthews, Simon Grocott, Daniel Foisy, Rainer Kuschnig, Hugh Chesser, Alexander Beattie, Anatoly Borshchov (our friendly Russian Security official)

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Conclusion

When all is said and done, there are both positive and negative aspects that we have experienced concerning accessibility to space. One the one hand, there has been a negative impact on the cost and schedule or our program. Our launch is approximately 18 months later than was expected, and significant redesign and rework was required that resulted affected the cost of our program.

However, there is a very positive outlook as well. A wide selection of Russian launch vehicles from which we have used the Rockot provided by Eurockot Launch Services, have greatly increased access to space. Without the Russian launch opportunities, our program would have been further delayed as we would be tied to the Radarsat-2 launch. Because our satellite once designed required a dawn-dusk sun synchronous orbit, the only other alternative would have been to find another primary going to such an orbit and hitchhike with it. However, this orbit is used little enough that there were few other opportunities. Without the accessibility provided by the Russian launch vehicles, our program would have suffered further delays and cost significantly more as a result.

Acknowledgments

References

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